Measurements of Stimulated-Raman-Scattering Instability Relevant to Ignition Hohlraum Plasmas

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Introduction

Control of laser-plasma instability is important for the success of laser fusion,[1] particularly indirect drive.[2] For indirect drive, laser beams enter a cavity (called a hohlraum) made of a material that has a high atomic number and that reaches a high ionization state (high Z). The high-Z plasma efficiently converts laser energy into x-rays, which in turn drive the implosion of a fusion capsule. Ignition hohlraums, such as those planned for the National Ignition Facility (NIF),[2] are expected to contain underdense plasmas (a few millimeters in size) with electron temperatures (T_e) in the kiloelectronvolt range. Present NIF hohlraum designs rely on the plasma pressure from a helium-hydrogen gas fill to tamp intrusion into the hohlraum volume by the gold-wall plasma, while allowing laser propagation inside the hohlraum.[3] Thus, the longest scale lengths are expected to be within the low-Z helium-hydrogen plasma.

Because scientists lack a fundamental understanding of many aspects of laser-plasma instabilities, it is desirable to study these instabilities in plasma conditions that are as close as possible to those expected in NIF hohlraums. Radiation-hydrodynamic simulations of NIF hohlraums[4] with the LASNEX code[5] (an inertial confinement fusion [ICF] design code) indicate that a variety of plasma conditions will exist within the NIF hohlraum. Not all of these conditions can be studied. Both inspection and postprocessing of LASNEX simulations of NIF hohlraums[6] show that it is clearly worth considering the millimeter-scale plasmas, with low Z, $n_e / n_c \approx 0.1$, and $T_e \approx 3$–5 keV expected in NIF-hohlraum plasmas (n_e is the electron density and n_c is the critical density above which the laser's light cannot propagate). Present lasers cannot reproduce all of the required conditions simultaneously, but they can approach the conditions so that useful data can be obtained.

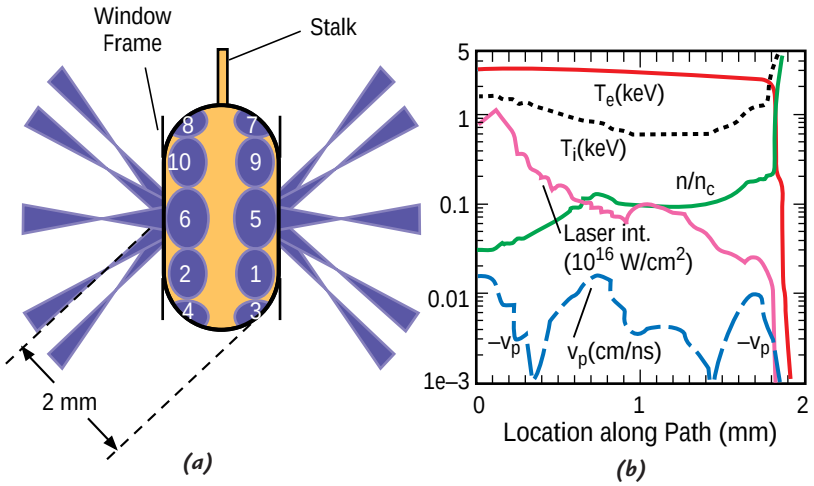

Fig. II-20. (a) An illustration of the gas-filled hohlraum. The footprints of the 10 Nova beams incident on the inner wall are indicated; those on the far wall have a dashed outline. (b) Calculated profiles within the hohlraum along a beam path (starting at the laser entrance hole) are plotted for a time of 1 ns.

Plasma Conditions

In this article we discuss the results obtained with toroidally shaped hohlraums,[7,8] which approach NIF conditions when illuminated with the Nova laser at Lawrence Livermore National Laboratory.[9] These targets were designed by X Division and fabricated by MST Division, and the experiments were fielded by P-Division scientists at Los Alamos. An illustration of the hohlraum is shown in Fig. II-20, reproduced from Fig. 1 of Ref. 7. It is cylindrically symmetric with a length of 1.6 mm and a diameter of 3.2 mm. All 10 laser beams operate at a wavelength of 351 nm. In the toroidal hohlraum we have used various gas fills, contained by thin, 0.3-μm-thick silicon nitride windows covering the laser entrance hole (LEH). Typical fills are low-Z gases such as C_5H_{12}, C_5D_{12}, CF_4, and $CF_4 + C_5H_{12}$ mixtures at 1 atm of pressure, designed to fully ionize to $n_e / n_c = 0.11$. They span the range $Z_{eff} = 2.5$–8. The calculated spatial profiles of n_e, T_e, T_i, and plasma-flow speed (v_p) along the direction of laser propagation ($\hat{k}_0$) for C_5H_{12} are also shown in Fig. II-20. For C_5H_{12}, $T_e = 3$ keV has been measured,[7,8] which is in agreement with LASNEX simulations. From Fig. II-20, the scale lengths for density, $L_n \equiv n_e / (\hat{k}_0 \cdot \nabla n_e)$, and velocity, $L_v \equiv c_s / (\hat{k}_0 \cdot \nabla v_p)$ are similar ($L_n \approx L_v \gtrsim 1$–2 mm). In the latter definition c_s is the ion-acoustic speed.

Laser-Plasma Instability

In the long-scale NIF plasmas, high levels of laser-plasma instability are predicted by linear convective theory.[10] Stimulated Raman scattering (SRS)[11] and stimulated Brillouin scattering (SBS),[12] in particular, could be significant. SRS and SBS involve scattering of laser light by electron-plasma (Langmuir) waves and ion-acoustic waves, respectively. From the initial noise level, these unstable waves would develop a growing amplitude in space. The backscattering direction is expected to have the highest spatial gain. The calculated gains from linear theory, even assuming smooth laser beams, are generally enormous (exp[25]–exp[30]) in plasmas such as ours,[6] and nonlinear saturation mechanisms are expected to occur. The high-energy glass-laser beams used for ICF are not spatially uniform. They have a broad distribution of intensities about the average value. Without any beam modification, these nonuniformities appear mostly as relatively large scale spatial fluctuations, with dimensions nonnegligible relative to the beam diameter.[13] Spatial smoothing can be accomplished with a binary random-phase plate (RPP),[14] which breaks the raw beam into smaller beamlets with a random 0 or π phase delay. RPPs produce a spatially "smooth" focal spot envelope with a superimposed fine-scale speckle (or "hot spot") pattern. The statistics of RPP hot spots are well known,[15] and it is clear that a significant fraction of the beam energy is tied up in hot spots. The known RPP hot-spot statistics allow better theoretical modeling of SBS and SRS in real plasmas, which recently has been successfully done by T-Division scientists.

SRS Onsets

We have verified that laser hot spots change the character of SBS and SRS instability onsets relative to theoretical predictions for smooth beams. With smooth beams, convective amplification of thermal density fluctuations would yield an SRS reflectivity that depends exponentially on laser intensity and L_n (≈ plasma size). But in the fluid model in Ref. 16, which is applicable to SBS and SRS in NIF conditions, instability gain on hot spots is computed including effects such as beam diffraction and pump depletion. Including diffraction is important because it can significantly decrease the spatial gain within a hot spot when the beam *f*-number is moderately small.[16,17] When the results are integrated over the RPP hot-spot distribution, the system becomes nonlinear and exhibits critical behavior. To understand the implications of the model in Ref. 16, one may consider a plasma with a sufficiently long L_n or L_v and a given seed or noise level of electrostatic waves (acoustic for SBS, Langmuir for SRS) that are sufficiently damped. We define the amount of laser light backscattered by such a seed in terms of its reflectivity R_{seed}. As the averaged intensity I of the beam envelope is increased starting from a value below the onset of instability, the laser reflectivity R sharply increases from R_{seed} once a critical intensity I_c is exceeded. The critical intensity is given approximately by the value of I, at which the linear convective gain ($R/R_{seed} = \exp[G]$) is approximately e^1 over the typical length of a hot spot, $l_{hs} \approx 7f^2\lambda$. This stands in contrast to the value $G = 2\pi$ of the gain exponent customarily taken as the threshold for significant convective instability. According to the model, even if we start with the minimum seed given by thermal density fluctuations (typically $R_{seed} \approx 10^{-8}$), once I increases moderately beyond I_c, then most hot spots undergo pump depletion (all the light is scattered) and R levels off.

We have investigated SRS onsets by varying I and measuring the SRS reflectivity from toroidal hohlraums filled with 1 atm of C_5H_{12}.[18] Figure II-21 shows the results. As with SBS, as I increases above a value I_c (about 10^{14} W/cm^2 in this case), the SRS reflectivity rises steeply and saturates at about 20%. Figure II-21 includes a fit to the data using the model in Ref. 16. The observed value of I_c for SRS is consistent with our best theoretical estimate.

The concept of a critical intensity for parametric instability seems to be fairly robust in long-scale plasmas. The critical intensity for SBS also has been measured both in the Nova toroidal hohlraums[7] and in Trident open plasmas.[20] The magnitude of I_c for SBS is predicted by the model in Ref. 16 to a reasonable approximation for a variety of plasma conditions.

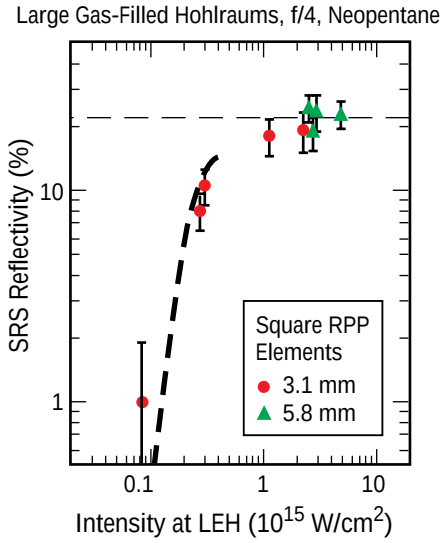

Fig. II-21. A plot of the SRS reflectivity into the interaction-beam cone, integrated over time, versus the interaction-beam intensity at the hohlraum laser entrance hole. The uncertainty in the beam intensity is approximately ±10% of its value.

SRS-Saturation Scaling

We have studied SRS saturation in the toroidal Nova hohlraums. For laser-intensity values similar to those in present NIF designs, it is observed that SRS is in a saturated state so that further increases in laser intensity do not yield a higher beam reflectivity. It is also observed that the SRS reflectivity depends on the damping rate of ion-acoustic waves (IAW), which is normalized to the real ion-acoustic frequency (ν_i/ω_i). Because SRS does not involve IAWs directly, this dependence may seem paradoxical. However, SRS can couple to other processes by further parametric decay of the SRS daughter electron-plasma wave, or SRS Langmuir wave (LW). The leading candidate is the Langmuir Decay Instability (LDI), in which the SRS LW further decays into an IAW and another LW,[22] as seen experimentally.[23] For a sufficiently strong laser drive, LDI daughter LWs themselves undergo LDI decay, creating so-called Langmuir turbulence. Langmuir turbulence is also relevant to ionospheric plasmas.

The dependence of SRS reflectivity on ν_i/ω_i has been studied with various gas fills in toroidal hohlraums, all at 1 atm of pressure and all designed to ionize to $n_e / n_c = 0.11$.[21] Both ν_i and ν_e are dominated by collisionless Landau damping for the plasma conditions of interest. In plasmas with multiple ion species, Landau damping of acoustic waves depends on the relative masses of the ions.[24,25] We have explored this fact, using the hohlraum gas fill, to vary ν_i/ω_i in our experiments. Again, C_5H_{12}, C_5D_{12}, CF_4, and C_5H_{12} + CF_4 low-Z gas fills are used.

The time-integrated SRS reflectivity data are shown in Fig. II-22. The data in this figure clearly show that as acoustic damping increases, SRS reflectivity increases. The laser intensity at the LEH is kept in the range of 2×10^{15} to 3.6×10^{15} W/cm^2. The observed scaling versus ν_i is consistent with the linear scaling predicted by a model of SRS saturation by Langmuir turbulence.[26]

SRS Images

It is very likely that SBS and SRS are spatially and temporally localized within the plasmas we study and do not have smooth, convective growth along the whole path of the laser beam within the plasma. In addition, it appears that SBS and SRS can mutually couple.[27–31] In order to resolve these issues, it is very desirable to image the scattered light in space and time and thus localize the SRS and SBS processes within the target. We have deployed two optical imaging instruments, the full-aperture-backscatter station imager (FABSI) and the axial imager at the Nova laser, to accomplish this task.[32,33]

In order to show the potential of SRS imaging as a density diagnostic, we show in Fig. II-23 an image of a conventional methane-filled, cylindrical Nova hohlraum using SRS light from the axial-imager diagnostic. We use the fact that the wavelength of SRS light depends on n_e. This type of hohlraum is used for studies of capsule illumination symmetry,[34] although this particular hohlraum has no capsule. The diagnostic was outfitted with a 550- to 650-nm band-pass filter, corresponding to n_e / n_c of 5%–15%. Out of the 2.2-ns pulse,

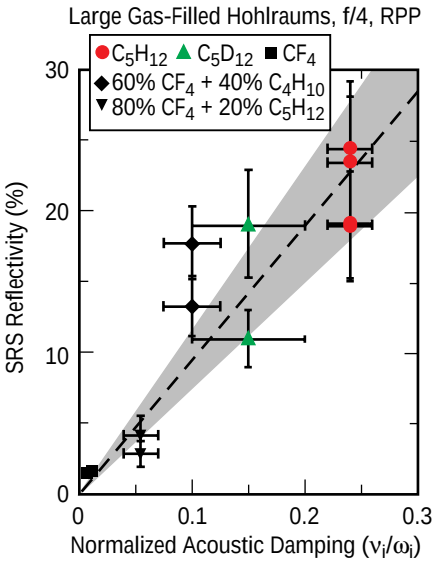

Fig. II-22. Raman backscatter reflectivities of the interaction beam for low-Z hohlraum gas fills. The least-squares linear fit (forced zero intercept) is shown. The shaded area shows the 95% confidence level for the fit.

the frame shown was gated for the 0.2- to 0.7-ns period. The image, when compared with the diagram on the bottom, shows that the LASNEX simulation predicts well the radial location of the 0.05-n_c density contour. However, although LASNEX correctly predicts a slight density buildup at the hohlraum axis, the observed density appears to be higher than the LASNEX prediction.

Summary

In summary, the speckled nature of laser beams used in ICF is an important factor in laser-plasma instability processes. For example, models that account for the laser speckles successfully predict the observed onsets of backscattering due to SBS and SRS. Linear convective theory predicts very large levels of SRS backscattering from the long-scale plasmas expected in ignition hohlraums. Our observations of SRS saturation are inconsistent with linear-theory scaling, but are qualitatively understood in terms of other processes. In particular, we have shown direct evidence for the dependence on acoustic damping of the SRS reflectivity. Since SRS itself is unrelated to acoustic waves, this dependence is evidence of other parametric processes determining the nonlinear saturation of Raman backscatter. We have great expectations from optical imaging diagnostics recently deployed at Nova. They could help elucidate important outstanding questions relating to SBS and SRS nonlinear saturation and could also prove to be a valuable density diagnostic.

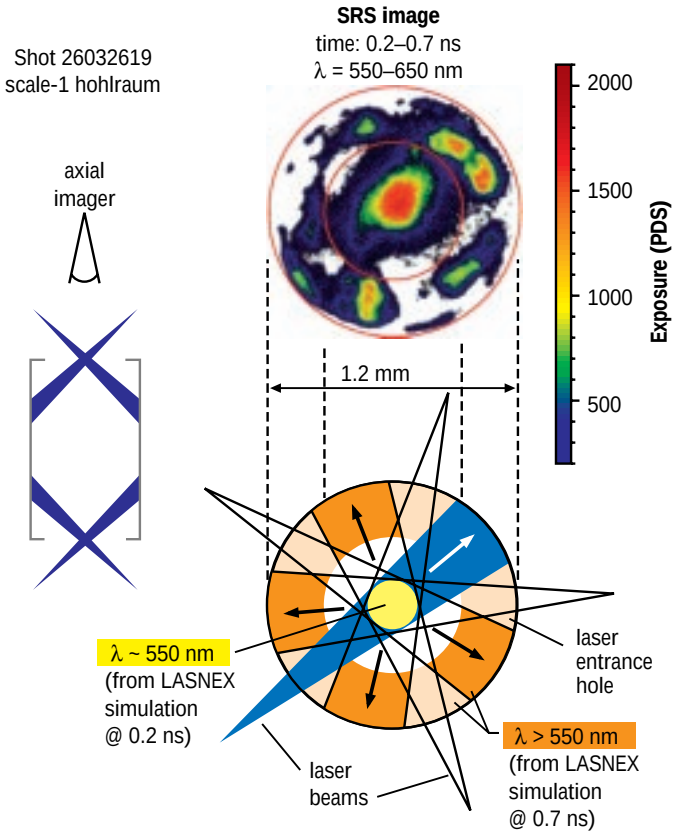

Fig. II-23. An image of the Raman scatter from a methane-filled scale-1 Nova hohlraum. The diagram on the left shows a side view of the hohlraum illumination geometry and the imager line of sight. The diagram on the bottom shows the hohlraum view from the imager location.

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